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16. Abstract

The model for the Io oxygen cloud have been improved and is now capable of calculating the two-dimensional sky-plane intensity for the 6300Å, 1304Å and 880Å lines, where volume excitation and ionization rates are determined by impact collisions with Io plasma torus electrons. These three emission lines are those for which observations have been performed by ground-based, rocket, Earth-orbiting satellites and Voyager spacecraft instruments. Comparison of model results with observations at 6300Å suggests an isotropic oxygen flux from Io of about (1.5-3.0) x 10^9 atoms cm^{-1} sec^{-1} or an overall source rate of (0.6-1.2) x 10^{27} atoms sec^{-1}. Several future refinements in the model will likely increase these values. Inclusion of change exchange ionization, for example, could increase the flux by an estimated factor of four to five and may provide an explanation for the Io correlated energy source discovered by Sandel (1981). A model for the expected but yet undetected Io sulfur cloud nas also been developed and very preliminary results are discussed. Quantitative analysis of the Io sodium cloud has focused upon the initial task of acquiring and preliminary evaluation of sodium cloud and Io plasma torus data.

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I. INTRODUCTION

Io is known to have an extended atmosphere of neutral sodium, potassium and atomic oxygen detected by ground-based observations and also appears to be the source of oxygen and sulfur ions forming a dense hot plasma torus threaded by the satellite orbit. This hot torus was recently discovered by the Voyager 1 spacecraft. Sodium atoms are supplied to the Io extended atmosphere or cloud with velocities at or above the escape velocity (~ 2.5 km sec^{-1}) and there is evidence for a broad dispersion in the emission velocity distribution up to 15 or 20 km sec^{-1} (Trafton and Macy, 1977). These velocities are highly non-thermal. The operative satellite emission mechanism for sodium atoms is not known but sputtering from Io's surface (Matson et al., 1974) and electromagnetic driven escape processes (Smyth and McElroy, 1977) have been suggested. Observational data available for the potassium cloud indicate that a satellite emission mechanism similar to sodium is likely (Trafton, 1981a). Little observational data are available for the oxygen cloud (Brown, 1981).

For the oxygen and sulfur ions in the hot Io plasma torus, the chemical identities of the initially ejected materials (e.g., O, S, SO, SO_2, NaS, S^+ etc.) and the nature of the satellite emission mechanism responsible for their ejection are at present poorly understood. Volcanic ejection velocities ($\lesssim 1$ km/sec) are too low for direct escape. For the sodium cloud, in contrast, a sufficient collection of ground-based data exists and has undergone sufficient modeling so that careful quantitative studies should now be able to somewhat completely and hopefully uniquely characterize the emission surface, flux and velocity distribution. This would then make it possible to identify the sodium emission process operative at Io. Although oxygen and sulfur escape from the satellite may not have the same escape mechanism as sodium, understanding the sodium mechanism would at least be highly suggestive and could be of fundamental importance. Understanding of the Voyager data for escape of oxygen and sulfur is presently at a much less advanced stage of development compared with sodium, but progress is rapidly being made with more data analysis. Detailed quantitative

analysis of Earth-based sodium data is therefore also of importance in this larger context. Simultaneous exploratory studies of the oxygen cloud and of a possible sulfur cloud are also desirable, especially in the light of recent advances in understanding their complex interactions with the magnetosphere.

The plasma conditions of the Jovian magnetosphere, determined both by Voyager and Earth-based measurements, are very important in understanding the sodium cloud or any other neutral potassium, oxygen or sulfur cloud emitted by Io. The spatial distribution of these emitted gases will of course depend on the nature and variability of the satellite source. It will, however, be influenced in addition by the plasma ionization lifetime of the orbiting atoms (or molecules) in the circumplanetary magnetosphere. If the lifetime is short, the gas should be relatively confined to the near satellite environment. On the other hand, if the lifetime is long, the orbiting gases will fill a doughnut shaped volume, extending all the way around the central planet (Fang et al., 1976). Spatial non-uniformities in the lifetime, as introduced by the presence of the Io plasma torus, will in addition non-uniformly contour the local density of the cloud.

The spatial distribution of gases in the extended Io atmosphere is also important in determining the characteristics of Jupiter's magnetosphere. As cloud atoms (or molecules) are lost through collisional ionization and charge exchange processes with the magnetospheric plasma, the newly created ions and electrons not only provide a net plasma source but also through neutral-ion charge exchange reactions actually alter to a significant extent the relative abundance of the ion species (Johnson and Strobel, 1982). This net source of plasma and these local alterations of the resident ion populations will then be spatially distributed in the magnetosphere by the corotational motion of Jupiter's magnetosphere and by magnetic diffusion processes, and will also be lost locally by ion recombination and by certain charge exchange processes with the neutral cloud atoms. The properties of the magnetosphere that are determined directly from analysis of plasma data obtained from the Pioneer and Voyager spacecraft and from Earth-based sites must ultimately be consistent with the magnetic diffusion and charge exchange processes of the satellite-ion source and also with the observations of

the neutral cloud densities in the near Io vicinity. This strong coupling of the Io plasma torus and the neutral cloud density, and the consistency of the measured and predicted properties of the magnetosphere are the subjects of primary concern to this research effort.

II. PROGRESS DURING THE FIRST YEAR

Goals and First Year Strategy

The two primary goals of this research program are (1) to characterize the satellite emission conditions of sodium, oxygen and possibly sulfur operative at Io, and (2) to help characterize the satellite-ion source and the magnetic diffusion of ions in the near Io environment. To achieve these two objectives, two different approaches have been initiated during the first year: (1) identification of the satellite emission characteristics for sodium atoms from the substantial neutral cloud data base obtained by Earth-telescope observations, and (2) exploratory modeling of the recently discovered Io oxygen cloud and a possibly existing Io sulfur cloud.

The strategy adopted during the first year has been to focus more effort upon the exploratory modeling of the Io atomic oxygen cloud and less effort upon the analysis of the Io sodium cloud data. This strategy was adopted to optimize our scientific program in response to reduced budgetary support available during the first year. The sodium data analysis effort has thus been restricted to acquisition and preliminary evaluation of Io sodium cloud and Io plasma torus data. This strategy has allowed the necessary ground work to be prepared in the first year so that the more time consuming and quantitative analysis of the sodium data may be initiated early in the second year.

Modeling of the Io Oxygen Cloud

Model Improvements

Significant progress has been made in the first year in exploratory modeling of the Io atomic oxygen cloud. The oxygen cloud model has been improved so that it is now capable of calculating not only the two-dimensional sky-plane intensity of the 6300Å emission of atomic oxygen (illustrated by earlier model results in Figure 1), but also the 1304Å emission and the 880Å emission of atomic oxygen. These three wavelength emissions are those for which observational measurements

have been performed by ground-based, rocket, Earth-orbiting satellite and Voyager spacecraft instruments as summarized in Table 1.

Improvements in the cloud model have also been made in the two-dimensional data for the Io plasma torus electrons. These data are used to determine the lifetime of oxygen atoms in the Jovian environment as well as the volume excitation rates for the three emission lines of atomic oxygen resulting from electron impact. The two-dimensional ionization lifetime for oxygen, produced by the Io plasma torus electrons and corresponding to the results of Figure 1, is shown in Figure 2. This lifetime is radially highly-asymmetric about the orbital position of Io ($5.9R_J$) such that the portion of the atomic oxygen cloud that forms inside the satellite orbital radius is significantly more dense and extended than the portion of the cloud outside of the orbit, as illustrated in Figure 3. The instantaneous oxygen-ion creation rate produced from this ionziation of the cloud atoms by the Io plasma torus is shown in Figure 4 and is (as expected) somewhat complementary to the spatial distribution of the neutral gas cloud shown in Figure 3.

Model Results for the Neutral Oxygen Cloud

The flux of oxygen atoms from Io can be determined by comparison of model results for the 6300Å emission intensity with the ground-based observation of Brown (1981). In our most recent calculations assuming plasma conditions appropriate to the encounter of Voyager 1 with Jupiter, Brown's measured value of 8 ± 4 Rayleighs corresponds to an oxygen flux of about $(3 \pm 1.5) \times 10^9$ atoms cm^{-2} sec^{-1} from Io's surface or an overall source rate of $(1.2 \pm 0.6) \times 10^{27}$ atoms sec^{-1}. This is 30% of the value assumed for the oxygen flux in the model results of Figure 1. For plasma conditions existing at the encounter of Voyager 2 with Jupiter (which are more appropriate to Brown's observations), the above values of the oxygen flux and overall source rate must be reduced by a factor of two.

These calculated values for the atomic oxygen flux and the overall source rate are only preliminary estimates which will be refined mostly upward in future calculations by incorporation of the four model improvements summarized in Table 2. Of particular importance is the third of

these four improvements, the inclusion of charge exchange lifetime processes for atomic oxygen. Relevant cross sections for neutral-ion and ion-ion charge exchange reactions for oxygen and sulfur have recently been estimated and their influence evaluated in the Io plasma torus by Johnson and Strobel (1982), who concluded that inside Io's orbit these processes are very important and are the primary means of ionizing the oxygen and sulfur gas clouds. The impact of including these charge-exchange processes in the above model calculation is roughly estimated to be an increase in the values of the required oxygen flux by about a factor of four to five. Efforts during the last quarter have already been initiated to update the model to include charge exchange. This update requires that the number density of the different ion species must be specified (included in the fourth improvement of Table 2) and eventually that the oscillating motion of the Io plasma about the satellite plane (the second improvement of Table 2) be incorporated in the model.

Specification of the oxygen atoms flux from the 6300Å intensity data automatically determines the intensity of the 1304Å emission and the 880Å emission in the model calculation. In our most recent model calculations, the intensity of the 1304Å emission is comparable to the 6300Å emission intensity, while the intensity of the 880 emission is about five times smaller. These model results for the UV emissions are a little below the observational upper limits imposed by measurements summarized in Table 1 when the different slit sizes of the measuring apertures on the sky plane are properly taken into account. More sensitive rocket and IUE satellite measurements or a longer analysis-sampling-time of select Voyager UVS data might therefore be able to provide a positive detection of one or both of these UV emission lines. This has been brought to the attention of the UV investigators.

Model Results for the Satellite Ion Source

Specification of the overall source rate of oxygen atoms emitted by Io from the analysis of the observed 6300Å intensity data also establishes the overall net O^+ ion-creation rate of the neutral cloud through electron impact ionization. Charge exchange reactions do not

change the net number of charges in the plasma although the number of charge carriers may be changed. The neutral cloud may not, however, be the only source of net O^+ ions for the Io plasma torus since direct escape of oxygen ions from the satellite or production of O^+ ions from dissociation of the oxygen bearing molecules or ions located in the Jovian environment might also occur. It would appear at present from the discussion to be presented below, that the satellite ion source provided by the neutral gas cloud is very significant if not, in fact, the dominant channel through which ions are supplied by the satellite to the magnetosphere. This understanding of the interaction of the satellite, its local atmosphere and its neutral gas clouds, and the magnetospheric plasma is of central importance since the fundamental conclusions that have emerged from recent observational and theoretical studies of Jupiter's magnetosphere are (1) that Io is the primary source of the Jovian magnetospheric plasma, and (2) that this plasma source is the key element that differentiates the character of the magnetosphere of Jupiter from that of the magnetosphere of the Earth and Saturn.

Model calculations of the spatial distribution of the atomic oxygen and satellite ion creation rate, as illustrated in Figure 3 and Figure 4, are useful in supporting many related studies of Jupiter's magnetosphere. Six such studies are summarized in Table 3 for which cooperative efforts with each investigator has been established. Results of the fifth cooperative effort is central in the recent work of Johnson and Strobel (1982) and the efforts reported here have benefited directly from the sixth cooperative effort (Smyth and Shemansky, 1982). Discussion here will be limited to the first subject in Table 3 for which some additional interesting results have been obtained.

The discovery of an Io-correlated energy source for the Io plasma torus was recently announced by Sandel (1981). His analysis of the Voyager UVS observations showed that the plasma downstream from Io is brighter in SIII 685Å emission because of an elevated electron temperature. The mechanism that raised the electron temperature was estimated to operate within about 45° of the position of Io in its orbit and represented a time average power input of about 4×10^{11} watts or about 20% of the power radiated in the UV by the torus. This time

average power input may well be associated with the spatial pattern of the instantaneous ion creation rate shown in Figure 4 if there exists an energy transfer mechanism that would rapidly thermalize the newly-created corotational ions and heat the plasma electrons. Using the overall net oxygen ion creation rate of 0.6-1.2 x 10^{27} sec^{-1} deduced from the oxygen cloud model and assuming that half that number of sulfur ions would also be produced near Io (similar to the results of Figure 4), a hot electron source located just ahead of Io's orbital position with an energy input of between 0.54-1.08 x 10^{11} watts or about 2.7%-5.4% of the total energy radiated in the UV torus would be produced if a rapid energy transfer mechanism were operative.

If the additional ionizations of the neutral oxygen and sulfur clouds produced by magnetospheric plasma charge exchange processes such as

$$O^+ + O \rightarrow O + O^+$$
$$S^{++} + O \rightarrow S^+ + O^+$$
$$O^+ + S \rightarrow O + S^+$$
$$S^+ + S \rightarrow S + S^+$$
$$S^{++} + S \rightarrow S^+ + S^+$$

were also included in the model, the overall oxygen supply rate and the overall ion creation rate are expected to be at least four to five times larger. In this case the model estimated value for the Io correlated energy source would then be between (2.2-5.4) x 10^{11} watts or between 11%-27% of the total energy radiated in the UV plasma torus, which is in reasonably good agreement with the 20% value reported by Sandel (1981). The remaining 80% of the input energy to the plasma torus has been associated by Shemansky and Sandel (1981a, b) with an electron-electon heating mechanism in the magnetosphere that is stationary in local time on the dusk side of Jupiter.

Modeling of the Io Sulfur Cloud

A model for the expected but not yet detected Io sulfur cloud was developed during the last quarter of this contract year. The lifetime of sulfur resulting from electron impact ionization and the volume

excitation rates for the sulfur emission lines at 4589Å, 7725Å, 10820Å and 11306Å resulting from electron impact excitation processes were incorporated in the model. Preliminary calculations indicate that the 4589Å line is about five times dimmer than the 7725Å line and that the 7725Å line is significantly dimmer than the 6300Å oxygen line emission from the Io plasma torus. The 10820Å line intensity is comparable to the 6300Å oxygen line emission intensity while the 11306Å line is somewhat dimmer. Complete sky-plane intensity maps of the sulfur emission intensities will be available early in the second year. Similar improvements to those listed in Table 2 for the oxygen cloud are also planned for the sulfur cloud model in the second year effort.

Analysis of the Io Sodium Cloud Data

The quantitative analysis of the Io sodium cloud data has been divided into five stages of activities which are summarized in Table 4. For model inversion of a given measurement, the sodium cloud model will be used to calculate a set of appropriate basis functions, which together with the measurement data, will then be the input for a constrained least square optimization problem. Best determined values of the physical model parameters will result from the data inversion method. The complete inversion scheme is diagrammed in Figure 5.

Efforts during the first year have been purposefully maintained at a low level because of budgetary reductions and have been restricted to the first stage of activity listed in Table 4, that of acquiring and preliminary evaluation of the old and new sodium cloud and Io plasma torus data summarized in Table 5. New line profile data for the sodium cloud have been recently obtained from Trafton (1981b). Additional line profile data are being sought from Trauger (1982) and spatial intensity data have been obtained from Mekler (1982). Improvements in the accuracy of plasma properties in the Io plasma torus are actively being sought from Bridge, Belcher, and Sullivan (1982) and from Pilcher and Morgan (1982).

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Table 1

Observational Data for the Io Atomic Oxygen Cloud

Type of Observation	Investigator	Emission Wavelength (Å)	Brightness (Rayleighs)
1. Ground Based	R.A. Brown	6300	8 ± 4
2. Rocket Flight	H.W. Moos	1304	?
3. IUE Satellite	H.W. Moos	1304	<6
4. Voyager UVS	D.E. Shemansky	1304 880	<25 <10

Table 2

Model Improvements for the Io Oxygen Cloud Model

1. Consideration of the effects of the velocity dispersion of the oxygen atoms emitted by Io, instead of assuming a mean emission speed

2. Introduction in the model of the oscillating motion of the Io plasma torus about the satellite plane, which is presently omitted

3. Inclusion of change exchange lifetime processes in the model for the oxygen cloud atoms, which are presently omitted

4. Improvement in the accuracy of values for the electron and ion number densities and their temperatures in the Io plasma torus

Table 3

Impact of Newly Created Ions: Magnetospheric Analysis

Subject	Investigator
1. Io-Correlated UV Energy Source	B. R. Sandel
2. Plasma Instability Energy Transfer Mechanism	R. A. Smith
3. Pick-up-Ion Field-Aligned Currents	W. H. Ip
4. Radial Diffusion of Plasma	G. L. Siscoe
5. Charge Exchange Processes in the Plasma Torus	D. F. Strobel

Table 4

Five Stages of the Quantitative Analysis of the Io Sodium Cloud Data

(1) acquiring and quality evaluation of the different Voyager and Earth-based data sets,

(2) performing suitable calculations using our highly developed numerical models to generate the appropriate (physical model parameter dependent) basis functions for analysis of selected observations,

(3) applying a simplex technique for non-linear optimization or a least squares technique with constraint optimization to each selected observation and its set of model basis functions for inversion and extraction of physical information,

(4) evaluating the compatibility of physical model parameters deduced from analysis of different observations, and

(5) performing consistent and simultaneous analysis of complementary data sets.

TABLE 5

Io Sodium Cloud and Plasma Torus Data

I. Voyager Data

Type	Description	Data Source
Plasma Data	energy and density information of Jupiter's magnetospheric ions and electrons in and beyond the Io plasma torus	H. S. Bridge (MIT)
UVS Data	upper limits measurements for ultraviolet emission from neutral clouds of Io and measured emission of oxygen and sulfur ions in the hot torus	D. E. Shemansky (SSI)

II. Earth-Based Data

Type	Description	Data Source
Plasma Data	energy and density information of Jupiter's magnetospheric ions and electrons in the cooler inner plasma torus	Published (Brown, 1976, 1978)
	same	C. B. Pilcher (Univ. of Hawaii; private communication)
Spatial Sodium Data	one-dimensional spatial intensity profiles measured through an observing slit	Y. Mekler (Univ. Ramat Aviv, Israel; private communication)
	same	R. A. Brown (LPL; private communication)
	average spatial intensity measured through an observing slit	Published (Bergstralh et al., 1975, 1977)
	average spatial intensity measurements north and south of Io observed through a slit	Published (Trafton and Macy, 1975; Trafton, 1977)
	average spatial intensity measurements east and west of Io observed through a slit	Published (Trafton and Macy, 1978)
	two-dimensional intensity images data	F. J. Murcray (Univ. of Denver; private communication)
Spectral Sodium Data	line profile shapes measured through an observing aperture or slit	J. T. Trauger (Cal. Inst. Tech.; private communication)
	same	Published (Trafton, 1975; Trafton and Macy, 1977)
	same	L. M. Trafton (Univ. of Texas; private communication)

Io OXYGEN TORUS 6300 Å EMISSION INTENSITY

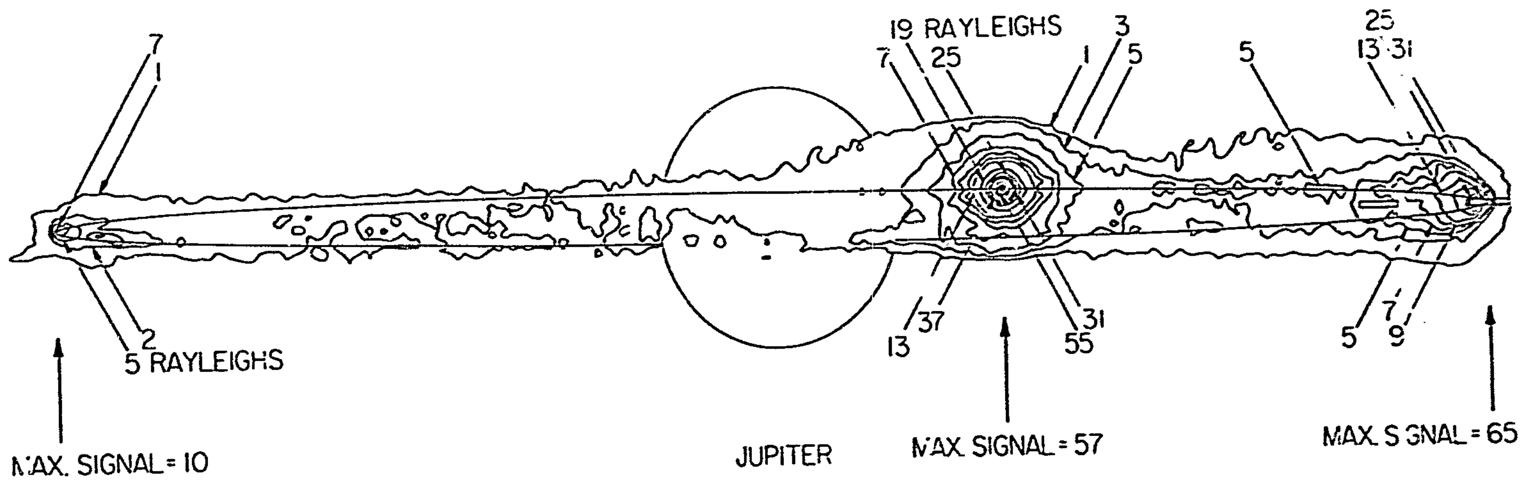

Figure 1

Model results for the 6300Å emission of the Io oxygen cloud are shown at the mid-point of the ground-based observation of Brown (1981). Isotropic emission from Io with a mean speed of 2.6 km/sec and with a satellite surface flux of 10^{10} oxygen atoms $cm^{-2}sec^{-1}$ were assumed in the model calculation. The rectangular observing slit of Brown is also shown to scale at the two positions for which measurements were made.

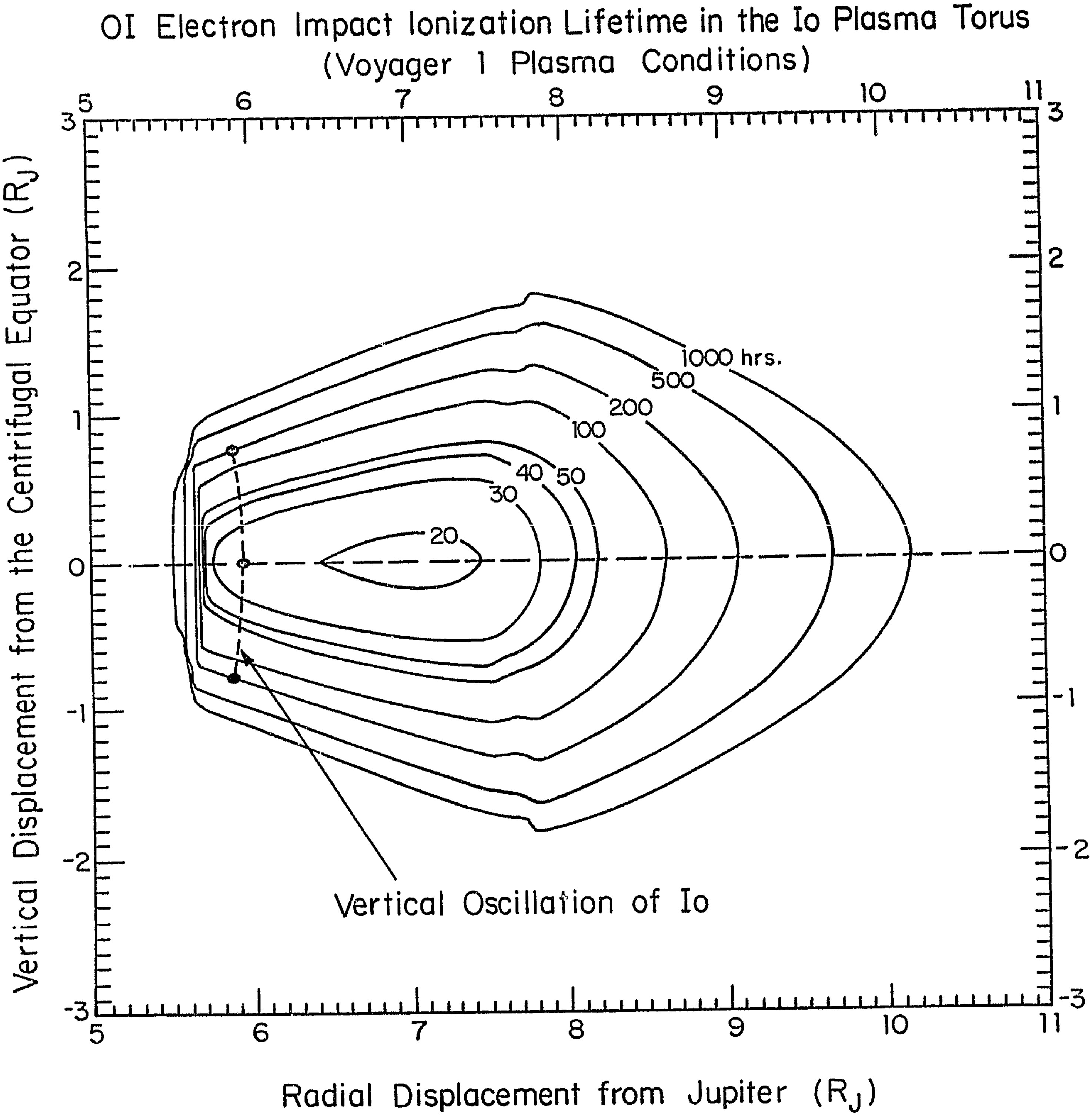

Figure 2

The two-dimensional lifetime of atomic oxygen in the Io plasma torus, calculated for electron impact ionization and assumed in the model results of Figure 1, is shown.

Io: Atomic Oxygen Torus

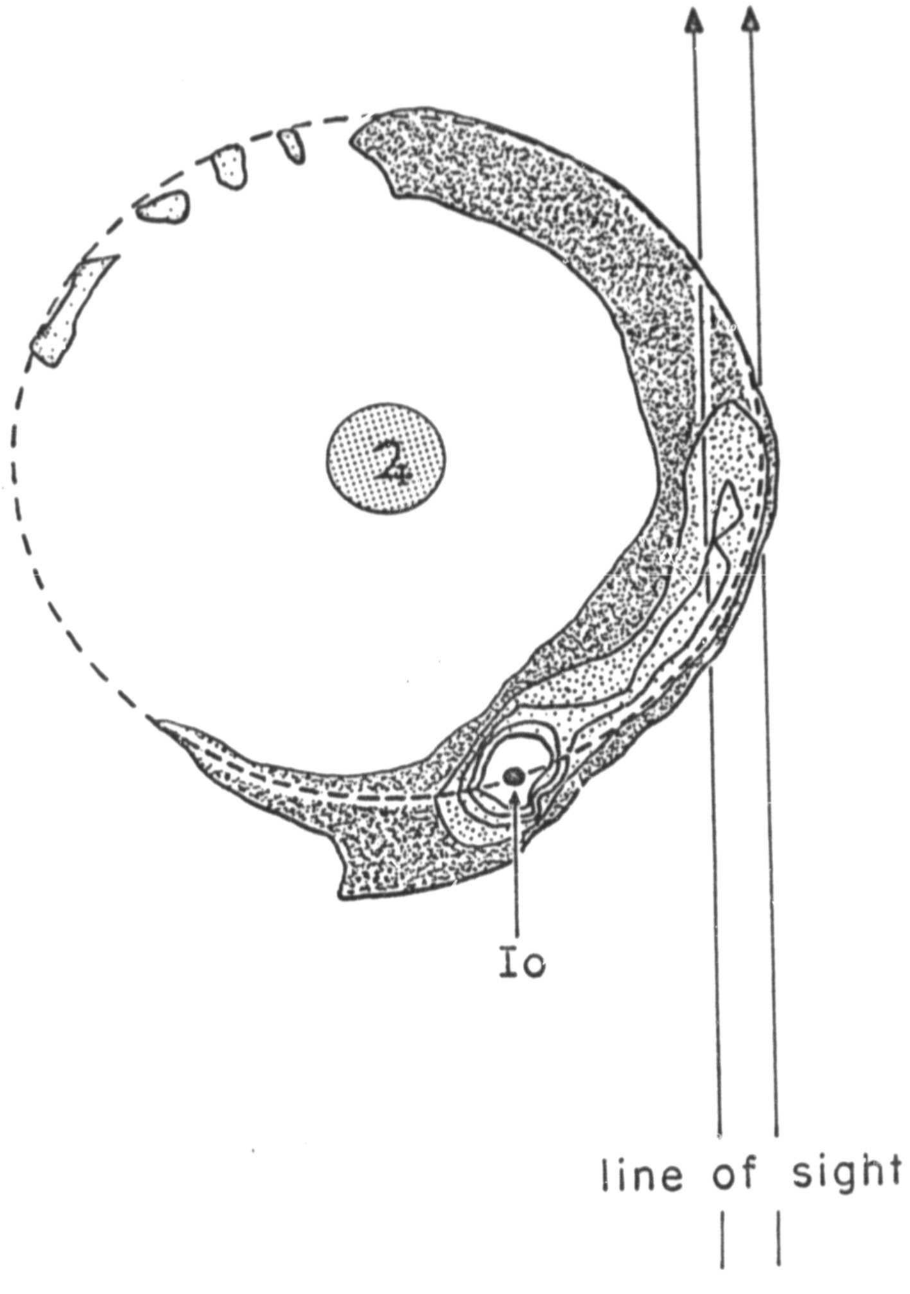

Figure 3

The two-dimensional column density (atoms cm^{-2}) of the Io oxygen cloud is shown as viewed above the satellite plane. Contour values near the satellite are larger.

Io: Oxygen Ion Creation Rate

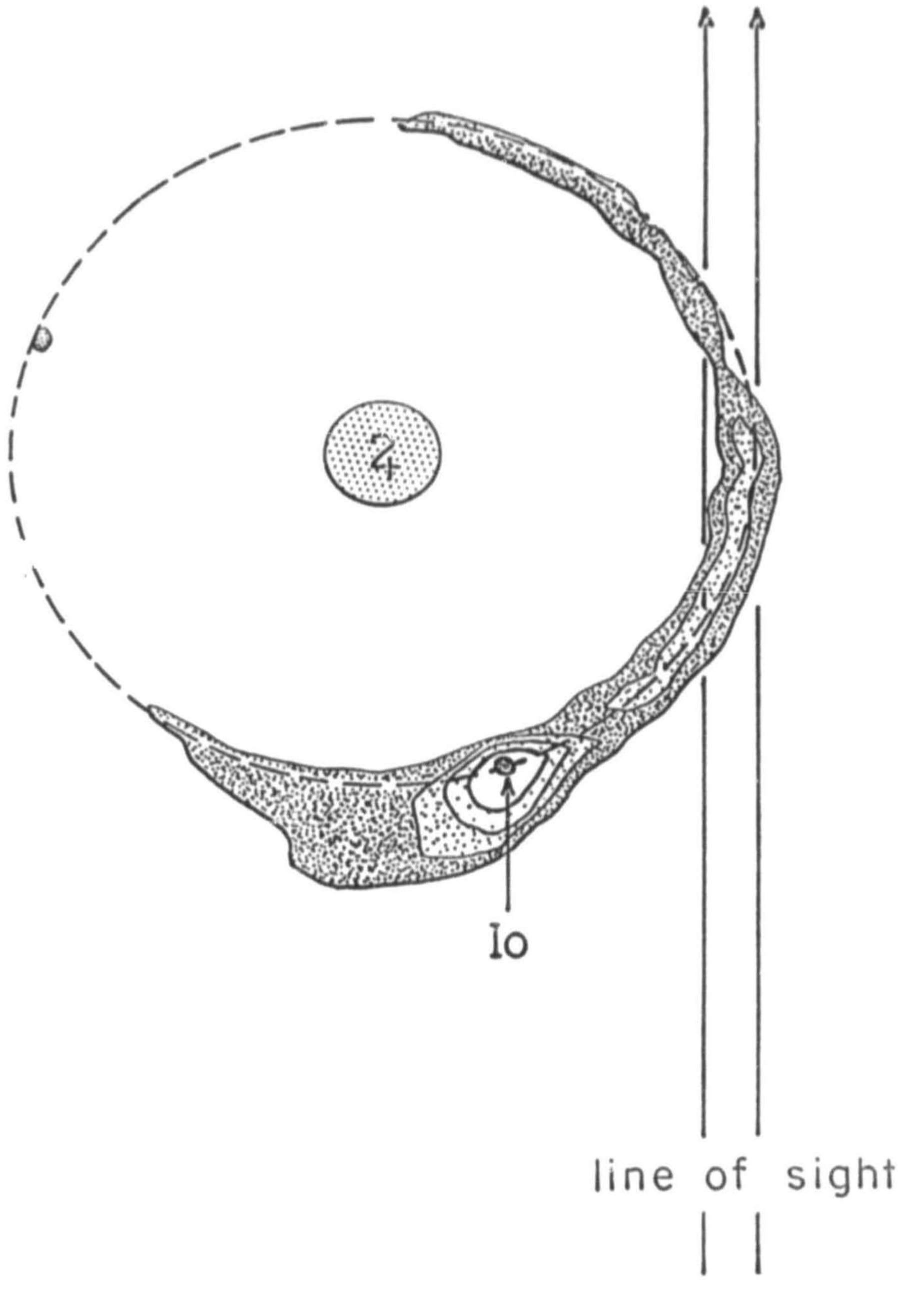

Figure 4

The two-dimensional oxygen ion creation rate (ions $cm^{-2}sec^{-1}$) produced by the interaction of the Io oxygen cloud and the model-assumed non-oscillating plasma torus is shown as viewed from above the satellite plane. Contour values near the satellite are larger.

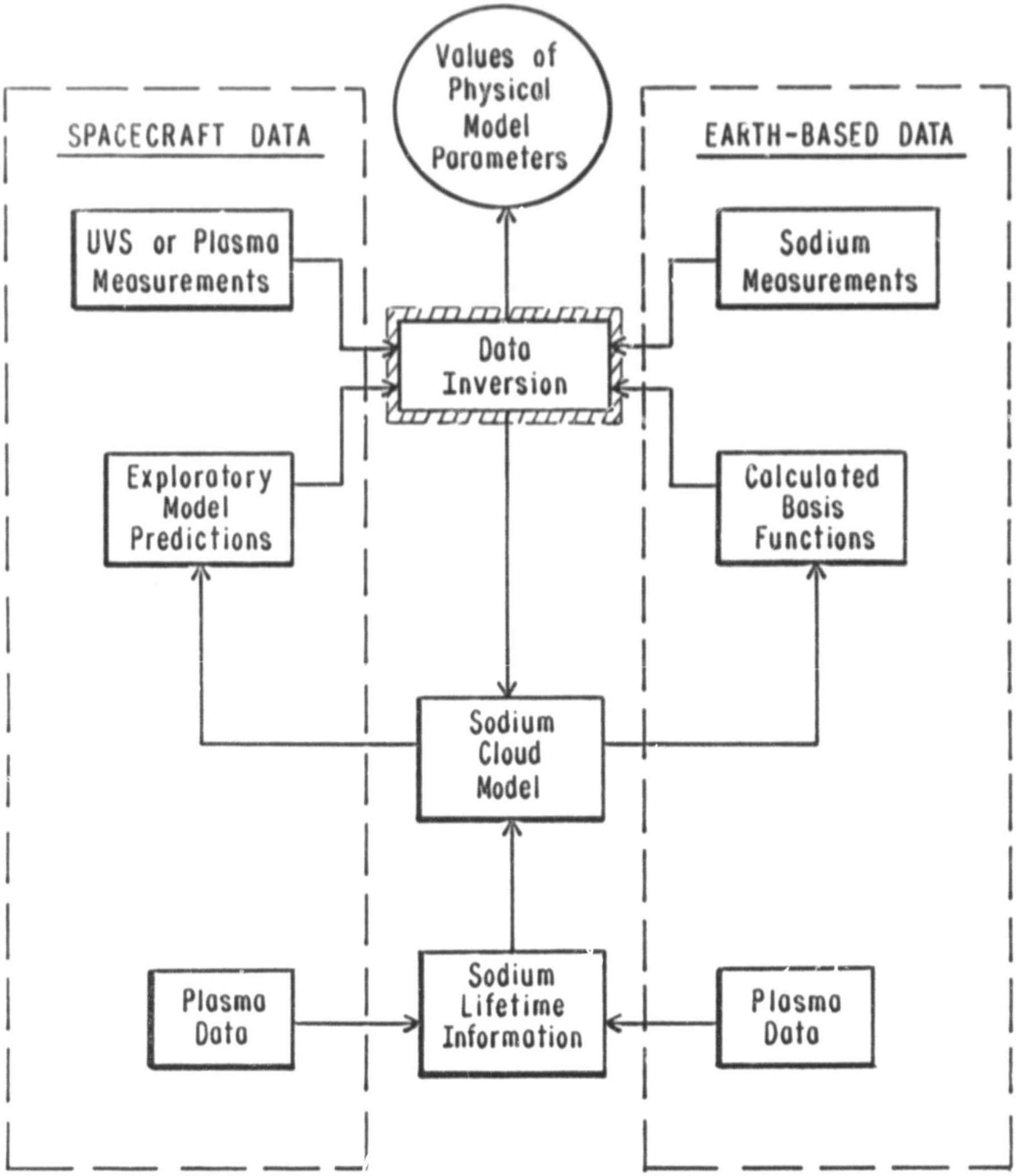

Figure 5

Data Analysis Scheme. The roles of the spacecraft and Earth-based data, the sodium cloud model, and the data inversion technique in determining the values of the physical model parameters are illustrated.